

# THE TACQ COMPUTER PROGRAM for AUTOMATIC TIME DOMAIN REFLECTOMETRY MEASUREMENTS: I. DESIGN and OPERATING CHARACTERISTICS<sup>1</sup>

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**Abstract.** *Despite the increased use of time domain reflectometry (TDR) for measurement of soil water content and bulk electrical conductivity (BEC), there are few public releases of software for TDR system control. The TACQ program, under development since the early 1990s on a wide variety of soils, allows control of multiplexed systems supporting up to 256 TDR probes. The program is DOS-based to ease creation of low-power, embedded computer systems; and to eliminate resource conflicts and timing difficulties inherent to multi-tasking, Windows-based operating systems. So that it can be easily used in embedded systems, the program was written to run with as little as 640 kbytes of RAM and 1 Mbyte of expanded memory, and with a variety of graphics standards and CPUs ranging from 80186 to Pentium. Embedded computer systems based on the PC-104 specification have been implemented using TACQ; and the program has been integrated into a supervisory control and data acquisition system (SCADA) for irrigation scheduling and control. Using a parallel port, the program controls multiplexers from both Campbell Scientific<sup>2</sup> (Logan, UT), and Dynamax (Houston, TX); and it allows reading of probes in any user-defined order if using the latter. The user has complete control over multiplexer address assignments, interconnection of multiplexers, and probe locations on each multiplexer; including individual settings for probe length, window width, averaging, distance to each probe, gain, and type of data acquired (waveform, travel time, apparent permittivity, water content, relative voltages for bulk electrical conductivity, or a combination of these). Interfaces to TDR instruments including Tektronix 1502 (modified), 1502B, and 1502C cable testers are implemented through an RS-232 port. Concurrent temperature data may also be acquired (ComputerBoards models CIO-DASx). System power control is implemented through the computer's own power management capabilities, and through direct control of power to the TDR instrument and video subsystem where applicable, thus allowing creation of very low-power systems. The program is stable and suitable for use in environmental measurement systems that are unattended for long periods of time. Waveform interpretation methods are discussed in the second paper in this series.*

**Keywords:** SCADA, TDR, Time domain reflectometry, Bulk electrical conductivity, Soil water content, Waveform interpretation, Soil temperature

Time domain reflectometry became known as a useful method for soil water content and bulk electrical conductivity measurement in the 1980s through the publication of a series of papers by Topp, Dalton, Dasberg and others (Topp et al., 1980; Dalton et al., 1984; Dalton and van Genuchten, 1986; Dasberg and Dalton, 1985; Topp et al., 1988). Automated TDR systems for water content measurement have been described by Baker

and Allmaras (1990), Heimovaara and Bouten (1990), Herkelrath et al. (1991), and Evett (1993, 1994). Commercial systems became available in the late 1980s and continue to evolve with TDR probes, multiplexers, and instruments available from a few companies, usually with proprietary and fairly rudimentary software interfaces embedded in proprietary data acquisition units. This paper describes the TACQ program for controlling an

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automatic TDR system. It begins with a discussion of aspects of the TDR method that influence program design, describes program design objectives, and discusses program capabilities and operation. Because waveform interpretation is a particular difficulty of the TDR method, the second paper in this series continues with a discussion of waveform shapes, factors that influence shape, and graphical algorithms for automated waveform interpretation.

In the TDR method, a very fast rise time (approx. 200 ps) step voltage increase is injected into a waveguide (usually coaxial cable) that carries the pulse to a probe placed in the soil or other porous medium. In a typical field installation, the probe is connected to the instrument through a network of coaxial cables and multiplexers. Part of the TDR instrument (e.g. Tektronix model 1502B/C) provides the voltage step and another part, essentially a fast oscilloscope, captures the reflected waveform. The oscilloscope can capture waveforms that represent all, or any part of, the waveguide (this includes cables, multiplexers and probes), beginning from a location that is actually inside the instrument and ending at the instrument's range (e.g. 600 m or about 5.5 microseconds for a Tektronix cable tester).

For example, Fig. 1 shows a waveform that represents the waveguide from a point inside the

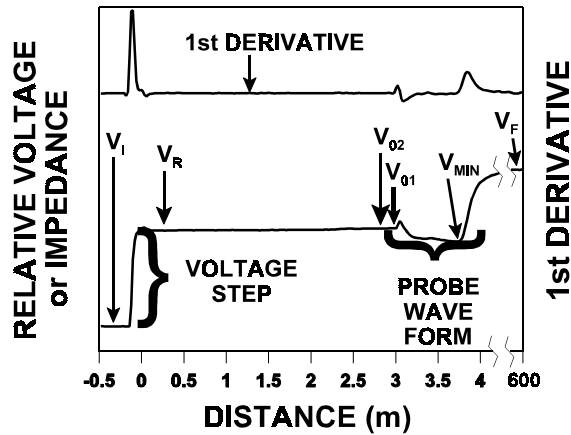


Figure 1. Plot of waveform and its first derivative from a Tektronix 1502C TDR cable tester set to begin at -0.5 m (inside the cable tester). The voltage step is shown to be injected just before the zero point (BNC connector on instrument front panel). The propagation velocity factor,  $V_p$ , was set to 0.67. The  $V_p$  value multiplied by the speed of light in a vacuum gives the speed of the signal in the coaxial cable connected to the instrument. At 3 m from the instrument a TDR probe is connected to the cable. The relative voltage levels  $V_i$ ,  $V_R$ , etc. are used in calculations of bulk electrical conductivity of the medium in which the probe is inserted.

cable tester, before the step pulse is injected, and extending beyond the pulse injection point to a point along the cable that is 4.5 m from the cable tester. The relative height of the waveform represents a voltage, which is proportional to the impedance of the waveguide. Although most TDR instruments display the horizontal axis in units of length (a holdover from the primary use of these instruments in detecting the location of cable faults), the horizontal axis is actually measured in units of time. The TDR instrument converts the time measurement to length units by using the relative propagation velocity factor setting,  $V_p$ , which is a fraction of the speed of light in a vacuum. For a given cable, the correct value of  $V_p$  is inversely proportional to the permittivity,  $\epsilon$ , of the dielectric (insulating plastic) between the inner and outer conductors of the cable

$$V_p = v/c_0 = (\epsilon\mu)^{-0.5} \quad (1)$$

where  $v$  is the propagation velocity of the pulse along the cable,  $c_0$  is the speed of light in a vacuum, and  $\mu$  is the magnetic permeability of the dielectric material. The amount of the waveform visible on the screen is determined by the distance per division setting, which determines the width of the instrument display in length units.

The TDR method relies on graphical interpretation of the waveform reflected from that part of the waveguide that is the probe (Fig. 2). An example of waveform interpretation for a 20 cm TDR probe in wet sand shows how tangent lines are fitted to several waveform features (Fig. 3). Intersections of the tangent lines define times related to (i) the separation of the outer braid from the coaxial cable so that it can be connected to one of the probe rods,  $t_1$ ; (ii) the time when the pulse exits the handle and enters the soil,  $t_1$ ; and (iii) the time when the pulse reaches the ends of the probe rods,  $t_2$ . The time taken for the step voltage pulse to travel along the probe rods,  $t_t = t_2 - t_1$ , is related to the propagation velocity as

$$t_t = 2L/v \quad (2)$$

where  $L$  is the length of the rods (Fig. 2), and the factor 2 signifies two-way travel.

For a TDR probe in a soil, the dielectric is a complex mixture of air, water and soil particles that exhibits an apparent permittivity,  $\epsilon_a$ . Substituting  $\epsilon_a$  and Eq. 2 into Eq. 1, and assuming  $\mu = 1$ , one sees that  $\epsilon_a$  may be determined for a probe of known

length,  $L$ , by measuring  $t_t$

$$\epsilon_a = [c_o t_t / (2L)]^2 \quad (3)$$

Topp et al. (1980) found that a single polynomial function described the relationship between volumetric water content,  $\theta_v$ , of four mineral soils and values of  $\epsilon_a$  determined in this fashion. Since 1980, other researchers have shown that the relationship between  $t_t$  and  $\theta_v$  is linear for all practical purposes (e.g. Ledieu et al., 1986).

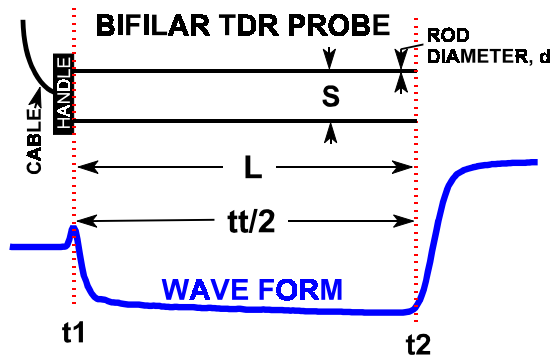


Figure 2. Schematic of a typical bifilar TDR probe and the corresponding waveform, illustrating probe rod length,  $L$ ; one way travel time,  $tt/2$ ; rod spacing,  $S$ ; and rod diameter,  $d$ .

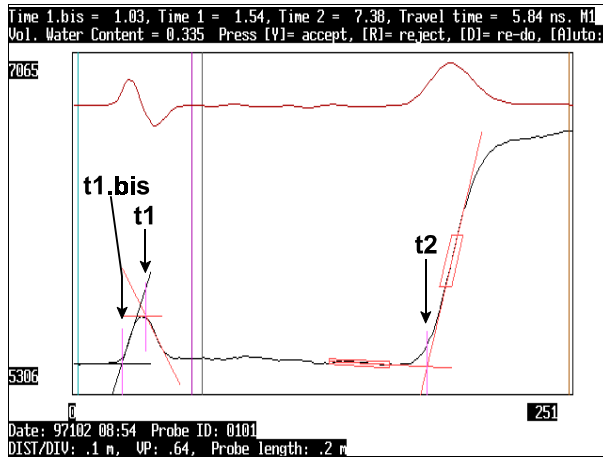


Figure 3. Example from TACQ of graphical interpretation of a waveform from a probe in wet sand. Vertical lines denoting times  $t1.bis$ ,  $t1$ , and  $t2$  have been marked by arrows and labels. The first peak in the waveform occurs just before  $t1$ . A horizontal line, drawn tangent to the waveform base line at the far left, intersects with a line drawn tangent to the first rising limb of the waveform to define  $t1.bis$ . A horizontal line drawn tangent to the peak intersects with a line drawn tangent to the descending waveform after the peak to define  $t1$ . Time  $t2$  is defined by the intersection of a line fitted to the waveform before  $t2$ , and a line fitted to the second rising limb of the waveform after  $t2$ . The water content is calculated from Eq. 7 of Topp et al (1980). The width of the waveform window is 1 m or  $1/(0.64 c_o) = 5.2$  ns. There are 251 data points in the waveform.

A program for automatic TDR data acquisition must be able to acquire the waveform from the probe and correctly interpret it graphically. It should be able to accomplish this despite different cable lengths to the probes, different probe lengths and rod spacings, and different soil conditions. Because soil temperature may affect TDR determinations of water content (Pepin et al., 1995; Verstricht et al., 1994), and because the effect may change with soil texture (Wraith and Or, 1999), it is important that a TDR data acquisition program also allow for acquisition of temperature data.

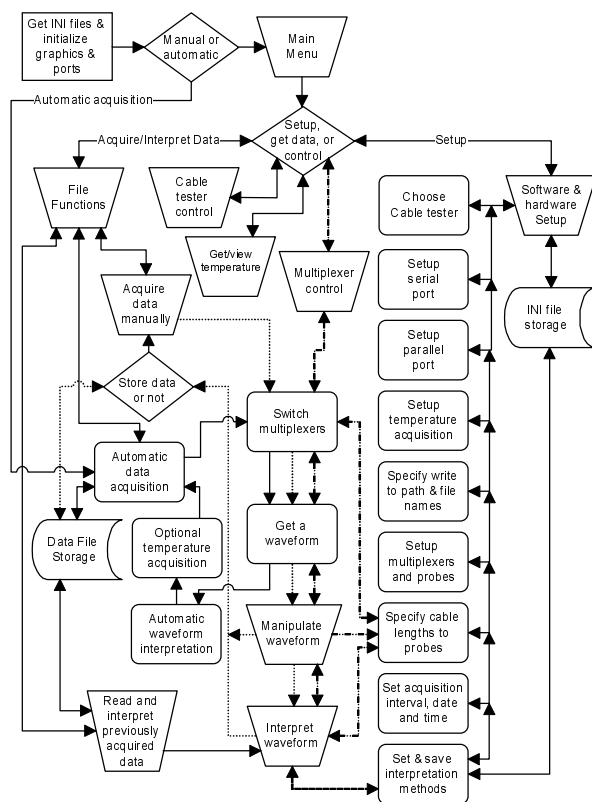
The objectives of this work were to create a computer program for TDR system control that would (i) work with the most commonly used TDR equipment including the Tektronix Metallic TDR cable testers and TDR multiplexers from Campbell Scientific (model SDMX50) and Dynamax (model TR200), and work with temperature data acquisition equipment (ComputerBoards model CIO-DASx and CIO-EXP32 multiplexers), (ii) allow individual waveform width and distance settings for any probe, (iii) acquire the relative voltage data needed for calculation of bulk electrical conductivity (BEC), (iv) run automatically, under user control, or when called by another program, (v) be suitable for use in embedded systems with limited memory and hardware support, and (vi) interpret waveforms from many different soils to give travel times and water contents. The last objective is addressed in the second paper in this series (Evet, 2000).

## HARDWARE and OPERATING SYSTEM COMPATIBILITY

The program has been used on IBM compatible computers with CPUs ranging from 80186 to Pentium, including laptop and notebook computers, and embedded systems using the PC-104 specification for IBM PC/AT compatible embedded computers. The program will run with as little as 640 kbytes of RAM and a floppy disk. However, one megabyte of expanded memory and a hard disk or other mass storage is recommended for better performance, and if waveforms are to be saved to file. Computers with a PC-CARD (PCMCIA) card slot may use an SRAM card, flash RAM card, or hard disk card to store data. Most subnotebook computers are equipped with such a slot and may be configured to boot DOS and run TACQ.EXE from an SRAM or flash memory PCMCIA card, thus eliminating the need for a hard disk or floppy disk,

For compatibility with a wide range of lower cost LCD panels and CRTs, the program is compatible with graphics standards at CGA and higher resolutions and will automatically configure graphics at the highest available resolution (EGA mode is used in VGA and higher resolution systems). A parallel port is required for control of multiplexers or control of power to the cable tester. A serial port is required to acquire data from the TDR cable tester. The program can automatically scan serial ports COM1 through COM4, and will find the cable tester if it is connected to the serial port, powered on, and selected in TACQ's Software Setup. If there are multiple serial and parallel ports, the user may specify which ports to use. TACQ will run with no cable tester connected if the user desires to interpret previously collected waveforms.

The program may be used in three main ways as illustrated by the flow chart in Figure 4 – software/hardware setup, control of hardware, and data acquisition (manual or automatic). First time users will need to setup the software to run with the particular TDR system hardware that they have installed. The cable tester, and serial and parallel ports are configured interactively, with the program automatically finding the cable tester on the serial port to which it is connected. File name extensions and the write path for file storage may be specified. Waveform interpretation methods may be set and saved from software setup or whenever a waveform is being interpreted (dashed line in Fig. 4). The connections between multiplexers (if any) and probes are specified, as are the cable lengths to each probe and probe rod lengths (In Fig. 4, dashed-dotted lines indicate how subprograms are used to accomplish this). If hardware for temperature data collection is available, it may be setup. The data acquisition interval and number of times to acquire data at each interval are also specified. Once the



**Figure 4. Flow chart of the TACQ program illustrating the main ways in which the program can be used - automatic or manual data acquisition, hardware control for debugging systems, and software and hardware setup of TDR systems. Different line types discriminate among these modes of use.**

hardware is setup, the user may opt for manual or automatic data acquisition. In manual mode, either single waveforms from chosen probes may be acquired, or waveforms from all probes may be acquired at once. Previously acquired waveform data files may also be accessed, and re-interpreted either manually or automatically. Dotted lines indicate how common subprograms are used in manual mode to interpret waveforms and store results; or to acquire, manipulate, and interpret waveforms and store results (Fig. 4). In automatic mode, the system will acquire all specified waveform and temperature data at each acquisition interval. Automatic mode may be entered by the user, or may be entered when the program is run from the command line with a command line instruction. This allows the program to go into automatic acquisition mode at boot up. Another command line switch allows the program to be called by a supervisory program, acquire all specified data, and return control to the supervisory program. Manual control of the multiplexers and cable tester are implemented for system debugging purposes, as is temperature data acquisition and viewing.

## FILE SYSTEM

A file directory facility allows the user to specify the path for output files. It is also used to find and specify files for input when TACQ is used to interpret previously acquired waveforms. Thus, the program can read waveform files archived, for instance, on a CDROM and write the output file of travel times, apparent permittivities, and water contents on a writeable drive somewhere else in the system. When specifying input data files, the user can tag one or many files and sort the files in the order in which they should be interpreted. Interpretation can be done automatically, but the user may intervene at any time, or interpret waveforms one at a time. Water content output files are sequential; but the user may take advantage of a transposition feature if the data are in regularly repeated form, as would be created during automatic data acquisition with a system of multiplexers and TDR probes. Using the transposition feature, the user may create a file of parallel output with all water contents for each data acquisition interval output on a single line. The transposed data are easily read into a spreadsheet for graphing water content vs. time for each probe.

The facility for specifying the path for output

files is also useful for redirecting output in embedded computer systems where TACQ is run from a small embedded flash or SRAM solid state disk. In these cases the embedded storage may be too small to hold much more than the operating system, TACQ, and its initialization files. So, output is redirected to outboard data storage such as a larger PC-CARD hard disk or flash disk, with the added advantage that these can be exchanged periodically.

Data files created automatically by TACQ are of four kinds; files containing waveforms and associated data needed for proper interpretation of the waveforms (e.g. Vp, distance per division, distance units, probe length); files containing water contents, travel times and apparent permittivities; files containing relative waveform voltages useful for calculation of bulk electrical conductivity, and temperature data files. Each file type is designated by a one letter code in its file name: T for waveforms, W for water contents, E for bulk electrical conductivity, and C for temperature. The water content files also contain the travel times and apparent permittivities, either of which could be used in a spreadsheet to compute water contents using a calibration equation of the user's choosing. New files are created each day. This prevents data loss of more than a day's data if there is a power failure or system crash during file I/O. The file system writes years as four digits to be year-2000 compatible.

Files for bulk electrical conductivity contain six data values that are the cable tester's digital representations of the waveform voltage at various points along the waveguide (Fig. 1). Several papers discuss how to calculate BEC from these data (e.g. Dalton, 1987, 1992; Dalton et al., 1984; Dalton and van Genuchten, 1986; Dasberg and Dalton, 1985; Nadler et al., 1991; Spaans and Baker, 1993; Topp et al., 1988; Wraith et al., 1993; Zegelin et al., 1989). The measured load impedance,  $Z_L$ , (ohms) is used in most methods of calculating bulk electrical conductivity:

$$Z_L = Z_{REF}(1 + \rho)/(1 - \rho) \quad (4)$$

where  $Z_{REF}$  is the output impedance of the cable tester (50 ohms), and:

$$\rho = E-/E+ \quad (5)$$

where

$$E^- = V_F - V_{O2} \quad (6)$$

$$E^+ = V_{O2} - V_I \quad (7)$$

and where  $V_{O2}$ ,  $V_I$ , and  $V_F$  are defined in Figure 1. For most methods only  $V_{O2}$ ,  $V_I$ , and  $V_F$  are needed. Because BEC calculation from TDR data is still a subject of active research, the other values are included for backward compatibility with methods of calculating BEC reported in the literature.

## HANDLING MULTIPLEXERS AND PROBES

Up to sixteen Dynamax TR-200 multiplexers (muxes) and 16 CSI SDMX-50 muxes may be individually controlled using six output lines of the parallel port. By default, the program assigns parallel port pins 2, 3, and 4 to the TR-200, and pins 6, 7, and 8 to the SDMX-50. However, any combination of the eight output pins (numbers 2 through 9) may be chosen by the user. For more than sixteen probes (more than 8 for the SDMX-50), muxes are usually connected in a tree configuration with a single primary-level mux connected to the TDR instrument, and two or more secondary level muxes connected to input channels of the primary mux. The TR-200 and SDMX-50 muxes are addressable, with the address of a mux set by moving jumpers on the circuit board (see Evett, 1998). Up to 256 probes may be connected to a multiplexer system if two of the secondary muxes share an address. Both secondary muxes will switch at the same time but only one will be connected to the active input channel of the primary mux.

By default, TACQ enables a primary mux, with input channel number one of that mux assigned to a TDR probe. Via the Software Setup menu, the user creates a virtual network of mux and probe connections that represents the actual network put in place for making measurements. During automatic or manual data acquisition, this virtual network guides the software in controlling the muxes to switch the correct probe into connection with the TDR instrument before a reading is acquired. The user specifies which channels of each mux are connected to other muxes or to probes, and which channels are not used. Multiplexer addresses and model (SDMX50 or TR-200) are specified as well. Because the TR-200 and SDMX-50 muxes are controlled via different sets of parallel port output lines, the two mux models may be used together in the same virtual and actual data acquisition system.

When specifying that a probe is attached to a particular input channel, the user specifies the probe length, and the type of data to be acquired as well. Two types of data are possible, (i) travel times, apparent permittivities, and water contents, and/or (ii) waveform level data for bulk electrical conductivity calculations. Either or both data types may be chosen, allowing conservation of file space and elimination of unneeded data. Because probe length may be specified, probes of different lengths may be used in the same system. This is often desirable where different layers of soil with differing properties are to be probed, or where mixtures of horizontally and vertically installed probes are used. Probe lengths from 5 cm to 150 cm have been used successfully.

## DISTANCE TO PROBE AND WAVEFORM WINDOW WIDTH

The TDR method relies on graphical interpretation of the waveform reflected from a probe in the soil or other porous medium. Instruments such as the Tektronix TDR cable testers can return waveforms that represent all, or any part of, the waveguide (this includes cables, multiplexers and probes) beginning from a location that is actually inside the cable tester and ending at the cable tester's range of 500 m. To correctly interpret the waveform reflected from the probe, the screen should display only the part of the waveguide that includes the probe. For this reason, the TDR instrument must be directed to acquire the waveform that represents the probe, not part of the cabling or multiplexers. The program provides an interactive window to facilitate finding and correctly positioning the probe waveform by manipulating distance,  $V_p$ , and distance per division (DIST/DIV) settings. The program recommends the best combination of  $V_p$  and DIST/DIV to set the window width for a probe of any particular length. Once these settings are made, the program will use them for future unattended, automatic data collection.

To date, there are no reports describing a method for setting the TDR window width that allows reproducible and consistent computerized determination of  $t_r$ . Yet, positioning has a direct effect on whether enough data are present to reliably fit lines to various portions of the waveform. Consider waveforms illustrated in Figs. 2 and 3. Because the data are digital representations of an analog phenomenon there are only a fixed number

of data pairs of voltage and time representing a screen of data. For instance, for the Tektronix model 1502B/C cable testers there are 251 data pairs. For Fig. 2 there were only four data pairs in the first rising limb, 12 data pairs in the first descending limb, and about 25 data pairs in the second rising limb. If similar waveforms were compressed horizontally, even by 50%, it would be difficult to find enough data points to reliably fit tangent lines to key parts of the waveforms. Thus, it is best to have the waveform occupy as much of the screen as possible. This is easily accomplished using the DIST/DIV and Vp settings of the cable tester. However, the width of the waveform increases with soil water content. If the window width is set when the soil is dry then the waveform may widen enough, with increasing water content, that the second rising limb is no longer included in the recorded waveform when the soil is saturated.

Fortunately, the desired screen width (ns) can be determined as follows. The apparent permittivity,  $\epsilon_a$ , is calculated using (Topp et al., 1980):

$$\epsilon_a = 3.03 + 9.3\theta_s + 146\theta_s^2 - 76.7\theta_s^3 \quad (8)$$

where  $\theta_s$  is the saturated water content. The saturated water content can be estimated from the soil dry bulk density,  $\rho_b$ . The total soil porosity is  $f = 1 - \rho_b/\rho_p$  where  $\rho_p$  is the particle density (assumed equal to 2.65). Assuming that all air is displaced when the soil is saturated, then  $\theta_s = f$ .

Equation 1 is re-arranged to calculate the velocity,  $v$ , of the signal in the waveguide

$$v = c_o(\epsilon_a\mu)^{-0.5} \quad (9)$$

And, travel time over the length of the probe is calculated from

$$t = L/v \quad (10)$$

where  $L$  is the probe length. Finally, additional time for the base line before the first peak and for the second rising limb after  $t_2$  is added to get the desired time to be represented by the full screen width. Experience shows that it is best to have at least one tenth of the screen width (one division) between the left hand side of the screen and the first peak, in order to reliably fit the base line (see Fig. 3). Also, it is best to have at least 0.2 of the screen width between  $t_2$  and the right hand side of the screen to reliably fit the tangent to the second rising

limb. To set the screen width, a combination of DIST/DIV and Vp settings is chosen that results in a full scale horizontal axis at least equal to the desired time.

**Table 1. Optimum propagation velocity factor (Vp) and distance per division (Dist/Div) settings and resulting screen widths in ns for several combinations of probe length and saturated water content. Settings give screen widths within 2% of those calculated using the assumptions in the preceding paragraph.**

Probe Length (m)	$\theta_s = 0.5$			$\theta_s = 0.4$			$\theta_s = 0.3$		
	Vp	Dist/Div (m)	Screen Width (ns)	Vp	Dist/Div (m)	Screen Width (ns)	Vp	Dist/Div (m)	Screen Width (ns)
0.05	0.59	0.025	1.40	0.69	0.025	1.20	0.85	0.025	0.98
0.10	0.59	0.05	2.80	0.69	0.05	2.39	0.42	0.025	1.96
0.15	0.39	0.05	4.20	0.46	0.05	3.59	0.56	0.05	2.94
0.20	0.59	0.10	5.61	0.69	0.10	4.78	0.42	0.05	3.92
0.30	0.39	0.10	8.41	0.46	0.10	7.18	0.56	0.10	5.87

**Table 2. Distance per division (Dist/Div) settings, and associated errors compared with optimum screen width, for Vp of 0.99 and for a range of saturated water contents and probe lengths. This is for a cable tester set for units of feet.**

Probe Length (m)	$\theta_s = 0.5$		$\theta_s = 0.4$		$\theta_s = 0.3$	
	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error
0.05	0.1	-27	0.1	-14	---	---
0.05	0.2	47	0.2	72	0.1	5
0.10	0.2	-27	0.2	-14	0.1	-48
0.10	0.5	83	0.5	115	0.2	5
0.15	0.2	-51	0.2	-43	0.2	-30
0.15	0.5	22	0.5	43	0.5	75
0.20	0.5	-8	0.2	-57	0.2	-48
0.20	1.0	83	0.5	7	0.5	31
0.30	0.5	-39	0.5	-28	0.5	-13
0.30	1.0	22	1.0	43	1.0	75

**Table 3. Distance per division (Dist/Div) settings, and associated errors compared with optimum screen width, for Vp of 0.70 and for a range of saturated water contents and probe lengths. This is for a cable tester set for units of feet.**

Probe Length (m)	$\theta_s = 0.5$		$\theta_s = 0.4$		$\theta_s = 0.3$	
	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error
0.05	---	---	---	---	---	---
0.05	0.1	4	0.1	21	0.1	48
0.10	0.1	-48	0.1	-39	0.1	-26
0.10	0.2	4	0.2	21	0.2	48
0.15	0.2	-31	0.2	-19	0.2	-1
0.15	0.5	73	0.5	102	0.5	147
0.20	0.2	-48	0.2	-39	0.2	-26
0.20	0.5	30	0.5	52	0.5	85
0.30	0.5	-14	0.2	-60	0.2	-51
0.30	1.0	73	0.5	1	0.5	24

The computer algorithm used by TACQ to find appropriate combinations of DIST/DIV and Vp, given the soil's saturated water content and the probe length, is given in Evett (1999).

Example results for several probe lengths and saturated water contents are given in Table 1. These results are for the Tektronix 1502B or 1502C cable testers, which allow variation of  $V_p$  settings in hundredths. The older Tektronix model 1502 cable tester gives the user just three  $V_p$  settings, 0.66, 0.70, and 0.99. When using the Tektronix 1502, TACQ gives two recommendations for Dist/Div (using the  $V_p$  value chosen by the user). The first recommendation will show a negative percent error, and the second will show a positive percent error. These are the percentage differences from the optimum screen width in ns. If the negative percent error is small, then the user may be able to use the corresponding Dist/Div recommendation. Otherwise, the user should use the Dist/Div recommendation that gives a positive percent error. This will result in a screen width in ns that is wider than absolutely necessary; but it will ensure that the second rising limb of the waveform is not lost off the right side of the screen when the soil becomes saturated. The user should use  $V_p$  values of 0.66, 0.70, and 0.99 and observe which value gives the smallest percent error. Tables 2 and 3 give some possible combinations of probe length and Dist/Div, and associated errors as a percentage of the optimum screen width in ns for  $V_p$  values of 0.99 and 0.70, respectively. These tables are given in units of feet because most of the model 1502 cable testers were built at the factory to use English units. For some combinations of probe length and saturated water content, there is no combination of Dist/Div and  $V_p$  settings that comes close to providing an optimum screen width with the model 1502 cable tester. This does not necessarily mean that good data cannot be obtained, but it does mean that the user may want to choose probe lengths that lend themselves more easily to optimization of screen width.

## TESTING

The program has been used to acquire water content and soil temperature data on a half-hourly interval at depths of 2, 4, 6, 10, 15, 20, and 30-cm in order to determine soil thermal conductivity as a function of water content (Evelt, 1994). It has been run by a supervisory program under MS Windows as part of a larger supervisory data acquisition and control system in an automated drip irrigation control system (Lascano et al., 1996). It was used to provide soil water content in the surface to 30-cm

layer for use in conjunction with deeper neutron probe measurements of soil water to compute wheat evapotranspiration by soil water balance, and allowed computed ET to match weighing lysimeter measurements to within 0.7 mm over a 16-day period (Evelt et al., 1993). The program has also been used to provide soil water content and temperature data in thin layers near the surface to test energy and water balance models, and to provide water content and temperature data above soil heat flux plates in order to correct heat flux measured at 5 cm to surface heat flux using the combination method (Howell et. al. 1993).

More recently, the program was used in a solar-powered PC-104 embedded computer system to measure a network of 64 TDR probes in a deep sand at Ismailia, Egypt. The probes had lengths of 30, 40, 50, 75, and 150 cm, and were arrayed to cover the surface to 300 cm depth range in six profiles (3 replicate measurements in each of two fields). Five Dynamax TR-200 TDR multiplexers were used. The PC-104 system consisted of an 80386SX module with 4 megabytes of RAM (WinSystems PCM-SX-33-4M) and a 4 megabyte flash memory chip acting as drive C: (M-Systems DiskOnChip 2000), a monochrome LCD module (WinSystems PCM-MPC-8-1) driving a Sharp LM64P839 display, a PC-CARD module accepting type I and II PC-Cards (M.K. Hansen PCM104-2-1) with a type II hard disk acting as drive D: for data storage, and a DC-DC converter module (WinSystems PCM-DC/DC-12-512) to provide 5 and 12 VDC regulated supplies to the computer system from the solar power system. Two Solarex 60 Watt solar panels were connected to two 12 VDC batteries and charging regulated with a Trace TR-C12. The LCD panel backlight was wired to a switch to reduce power consumption when unattended; and TACQ was configured to turn off power to the Tektronix 1502B TDR cable tester between measurement intervals. Data presented are for a period during which the system ran unattended from August 12, 1998 to Jan. 11, 1999 when a combination of low sun angle (Ismailia is at 30°36' N) and extended cloudiness caused the system to lose power.

To avoid clutter, water content data from just the top three and the bottom three depth intervals in one profile are shown (Fig. 5). The data cover the latter part of a maize irrigation season that was discontinued on Sept. 3 (day 246), a fallow period from Sept. 3 to Nov. 7, and the first part of a faba



bean irrigation season after irrigations were resumed on Nov. 7 (day 311) (Fig. 5A). A large irrigation on day 237 allowed the wetting front to be followed (Fig. 5B). It arrived at the 0.75 to 1.5-m depth interval on day 239, at the 1.5 to 2.25-m depth interval on day 241, and at the 1.5 to 3.0-m depth interval on day 244. Maize was harvested on Sept. 9 (day 252). During the fallow period, the three measurements near the soil surface approached 0.02  $\text{m}^3 \text{m}^{-3}$ . The three deep measurements approached steady values that were different depending on the depth. The 0.75 to 1.5-m layer dried more than the deeper layers, probably due to water extraction by corn roots, which can reach to 1.5-m depth. The two deepest measurements probably approached the “field capacity” for this soil, which thus can be estimated at about 0.06  $\text{m}^3 \text{m}^{-3}$ . Note the narrow range of water contents, which almost never exceed 0.10  $\text{m}^3 \text{m}^{-3}$ , even when heavily irrigated. After day 344, faba bean was irrigated every other day, causing the zig-zag pattern in the water contents at the upper three depths. Fluctuations in water content were more modest for the deeper measurements. The quick rise in water content in the 0.75 to 1.5-m

interval and the increase of water contents for the deeper measurements to well above “field capacity” were evidence of considerable deep percolation loss under the imposed irrigation regime. This led to a recommendation to switch from irrigation every other day to much smaller irrigations several times per day.

## SUMMARY

The TACQ computer program was developed to automatically control a stand-alone TDR system consisting of a TDR instrument, up to seventeen multiplexers, and up to 256 probes. Optionally, concurrent temperature data may be collected using thermocouples. The program is easily used in an embedded computer system and allows storage of data in removable media while running from a small solid state disk. It can control system power to allow low-power TDR systems including solar powered ones. The program will run under DOS and Windows (3.11 and 95 in DOS mode). The user has complete control over the waveform interpretation methods used, the acquisition interval, the kind of data acquired for each probe, and the interconnection of probes and multiplexers. Different cable lengths to probes and different probe lengths are accommodated easily in the same system. Data for water content, bulk electrical conductivity, and temperature measurements may be collected. The program is stable and suitable for use in environmental measurement systems that are unattended for long periods of time. The TACQ program, and complete TDR system documentation in Adobe PDF file format, may be freely downloaded from

<http://www.cprl.ars.usda.gov/programs/>.

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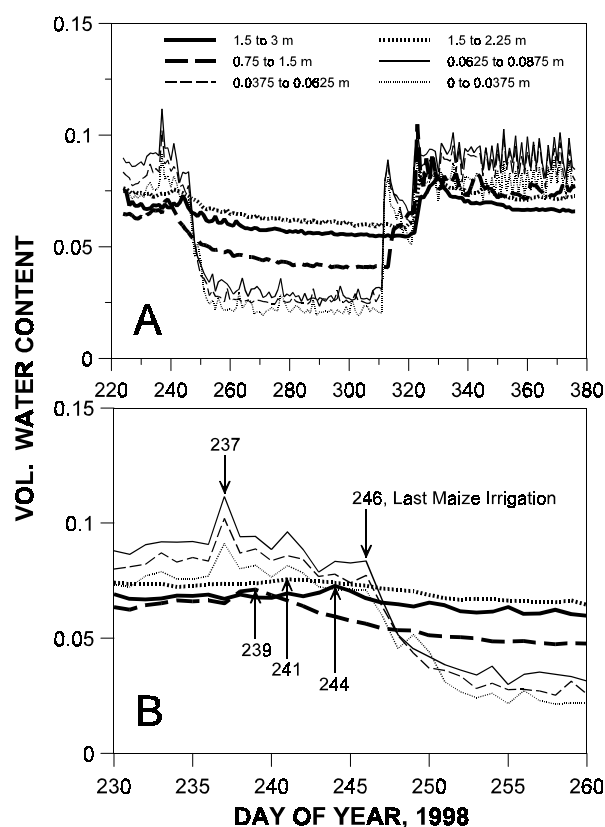


Figure 5. Water contents at six of eleven depths measured for profile #4 in the south lysimeter field at Ismailia, Egypt. Data begin on August 12, 1998 and end on January 11, 1999 (A). Maize irrigations were discontinued on Sept. 3 (day 246), and irrigations were resumed on Nov. 7 (day 311) prior to planting faba bean. A large irrigation on day 237 allowed the wetting front to be followed (B). It arrived at the 0.75 to 1.5 m depth interval on day 239, at the 1.5 to 2.25 m depth interval on day 241, and at the 1.5 to 3.0 m depth interval on day 244.

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